Femtosecond Transversal Deflection of Electron Beams with the Help of Laser Beams and Its Possible Applications

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Abstract

It is shown that the interaction of an electron beam with polarized electromagnetic wave of laser photons propagating in the same direction in a short interaction region results in significant transversal deflection of the electrons which can be used for production of femtosecond electron and synchrotron radiation beams, for chopping the electron beams and construction of laser oscilloscopes measuring femtosecond processes.

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As it is well known (see [1] and references therein) it is difficult to accelerate the charged particles by the periodically varying electromagnetic field of laser photon beams, especially, in vacuum, because the fields are perpendicular to the direction of propagation of photons. Despite the fact that there are very strong fields of laser beams with intensity up to $W \simeq 10^{18} W/cm^2$ and electric field up to $E \simeq 2.10^{10} V/cm$ and optimistic acceleration rates theoretically predicted for various advanced methods of particle acceleration, the achieved record acceleration rates are less than $\sim 10^{10}$eV/cm at very short distances, and the progress in this field is very slow.

On the other hand there is a growing interest to the production and study of particle and photon bunches with ultrashort time duration connected with the advance of new acceleration methods, microbunching of particle beams, various radiation mechanism, etc. The latest achievements [2-4] of obtaining femtosecond pulses of synchrotron radiation with spectral distribution from infrared to hard X-ray regions using femtosecond laser pulses [5] open a possibility to study atomic, solid state, chemical and biological processes in a new fundamental time scale of $\sim$ 100 fs of the order of vibrational period of molecules.

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At present several methods has been developed for the measurement of subpicosecond times. The oldest one [6] based on the transverse deflection of electron beams by the field in RF cavity has been modified in many works and together with comercial streak cameras allow to study the bunch length and longitudinal particle distribution at time intervals up to ~ 100 fs. However these methods are expensive and the theoretical limits of these methods is less than 10 fs [6].

The existing other methods of the study of short processes use the properties of various types of coherent radiation the intensity of which is proportional to the square of the number of the particles in bunches [7,8] when the wavelength of the radiation becomes larger than the length of the bunch. With the help of autocorrelation information and possible phase data this method can be improved to measure time durations down to tens of fs. Moreover as it has been shown in [9] the study of the coherent x-ray transition radiation of microbunched beams theoretically allows to study processes with varying in time intervals down to atosecond, 10^{-18}s, nevertheless, the time measurement accuracy achieved by coherent radiation methods is of the order of few hundreds of fs. Thus there is a need for a method for the measurement of femtosecond times.

In this short note it is shown that despite to the difficulties of particle acceleration one can successfuly use the laser beams for the transversal deflection of electron beams.It is shown that by replacing the deflecting RF electromagnetic fields inside the cavities by intense laser fields one can construct subfemtosecond oscilloscopes.

Let us assume that an electron beam with relativistic factor $\gamma = (1-\beta^2)^{-1/2} = \varepsilon/mc^2 \gg 1$, ($m$, v, ε are the mass, velocity and energy of the electrons and $\beta = v/c$) enters a vacuum interaction region with length L_{int} where a plane monochromatic electromagnetic linearly polarized wave of laser photons with wavelength $\lambda = 2\pi c/\omega$ is propagating in the same direction. Just as in the case of particle acceleration, due to the difference between the light and electron velocities, the transversal deflection acquired by the electrons when the phase of the waves acting on the electrons are varied less than π, will be compensated by the opposite deflection during the next π variation of the phase. However, one can show that if L_{int} is much less than $\lambda\gamma^2$, and the difference between the entrance and exit phases is less than π the electrons will "feel" an almost constant electric

field E and will be deflected under certain deflection angle α depending upon the entrance phase. If the electric field of the traveling wave is close to its maximal, amplitude value $E \simeq E_0$ and the magnetic field $H \simeq 0$ than due to a short interaction time $t_{int} = L_{int}/2c$ assuming $E \simeq const$ ams $H \simeq 0$ one can show that the maximal deflection angle of the electrons is given by the formula

$$\alpha_{max} \simeq \frac{eE\lambda\gamma}{2mc^2\beta} = \pi\gamma\xi, \tag{1}$$

where $\xi = eE/mc\omega$. From (1) it follows that it is better to have larger wavelength (CO_2 laser with $\lambda = 10\mu m$), relatevistic electron beams, $\gamma \gg 1$. or $\beta \ll 1$. It also follows that in the case of nonrelativistic electron beams which usually have larger angular divergence the beam deflection is not realistic because L_{int} is small equal to the wavelength. If there is a screen on a distance L_{sc} after the interaction region then the electron beam will oscillate with maximal deflection $R_{max} = L_{sc}\alpha$.

For a photon beam with $E \simeq 6.3.10^4 V/cm$, which is provided by a relatively weak laser beam with intensity $W \simeq 10^9 W/cm^2$, $\lambda = 10\mu m$, (CO_2 laser beam with $\xi \simeq 0.0002$) and for relativistic electrons with $\gamma = 100$ (ε= 50 MeV) one obtains $\alpha = 0.06$ radian which is much larger than the angular divergence of such electron beams. Therefore taking $L_{int} = 5cm\lambda\gamma^2/2$ and $L_{sc} = 50$ cm the continuous electron beam will oscillate on the screen with an amplitude $R = 30$. The use of circularly polarized plane wave instead of linearly polarized wave or the addition of a second such a perpendicularly deflecting laser system with appropriate phase matching will sweep the contineous electron beam on a circle with a lenth $L \simeq 2\pi R = 18.85$ cm and with a period $T = \lambda/c \simeq 33$ fs. If the length T_e of the electron beam is less than T then only a part T_e/T of the circle will bombarded by electrons and shine. Measuring the length of the shining one can measure the length of the short electron pulses down to ten fs with accuracy of a few fs, i.e. construct femtosecond oscilloscopes.

It is worthwhile to make some remarks. It is well known [10] that in the electron rest frame the trajectories have the shapes of "eight" and circle in the cases of linearly and circularly polarized electromagnetic waves, respectively. The transversal sizes of the trajectories are small and are of the order of wavelength in the case of very strong fields equal to the critical ones $E_{crit} = m^2c^3/e\hbar = 1.3210^{16}$ V/cm. The relatively large sizes of

the figures on the screen is due to the angles (1) large with respect of the angular spread of the existing electron beams and large L_{sc}.The second remark concerns the velocity of the expansion of the shining of the screen figures which exceeds the light velocity in vacuun as ussually takes place in such devices.

Here we shall not consider the sufficiently high sensitivity of the proposed osciloscopes as well as the influence of various factors on the amplitude and time measurement errors. Let us only note that due to the very short times the number of electrons involved into the process of deflection is very low. Therefore the usual screens are not suitable for detecting the arcs and circles. Scintillation and other types detectors with sufficient mosaity which can detect single electrons or secodary electrons from the process under investigation [11,12] can serve for detecting the figure on the screen. However, in this case, as it is well known [6,11], the maximal attainable time resolution, $\sim 10^{-14}$ s, is determined mainly by the spread of the initial velocities and by the emission time of secondary electrons coming out from a thin layer of the electron source. Therefore the expected time resolution is slightly less than 10 fs, which is by one and two order order better than it is expected and achieved with the help of other methods.

What concerns the other application, namely, the production of SR femtosecond pulses the advantage of the proposed method in this case is in the fact that no insertion device in the interaction region is required. The proposed femtosecond sweeping of the electon beams, of course, can find many other applications as for shortening the electron beams by the well known chopping methods. These applications and more correct consideration of the problems will be given in an other publication. One of the authors (K.A.I) thanks H. Avetissyan and A. Margaryan for discussions. This work has been supported partially by ISTC A372.

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